Probing the Relativistic Shock Environs of Blazar Jets in the Fermi Era

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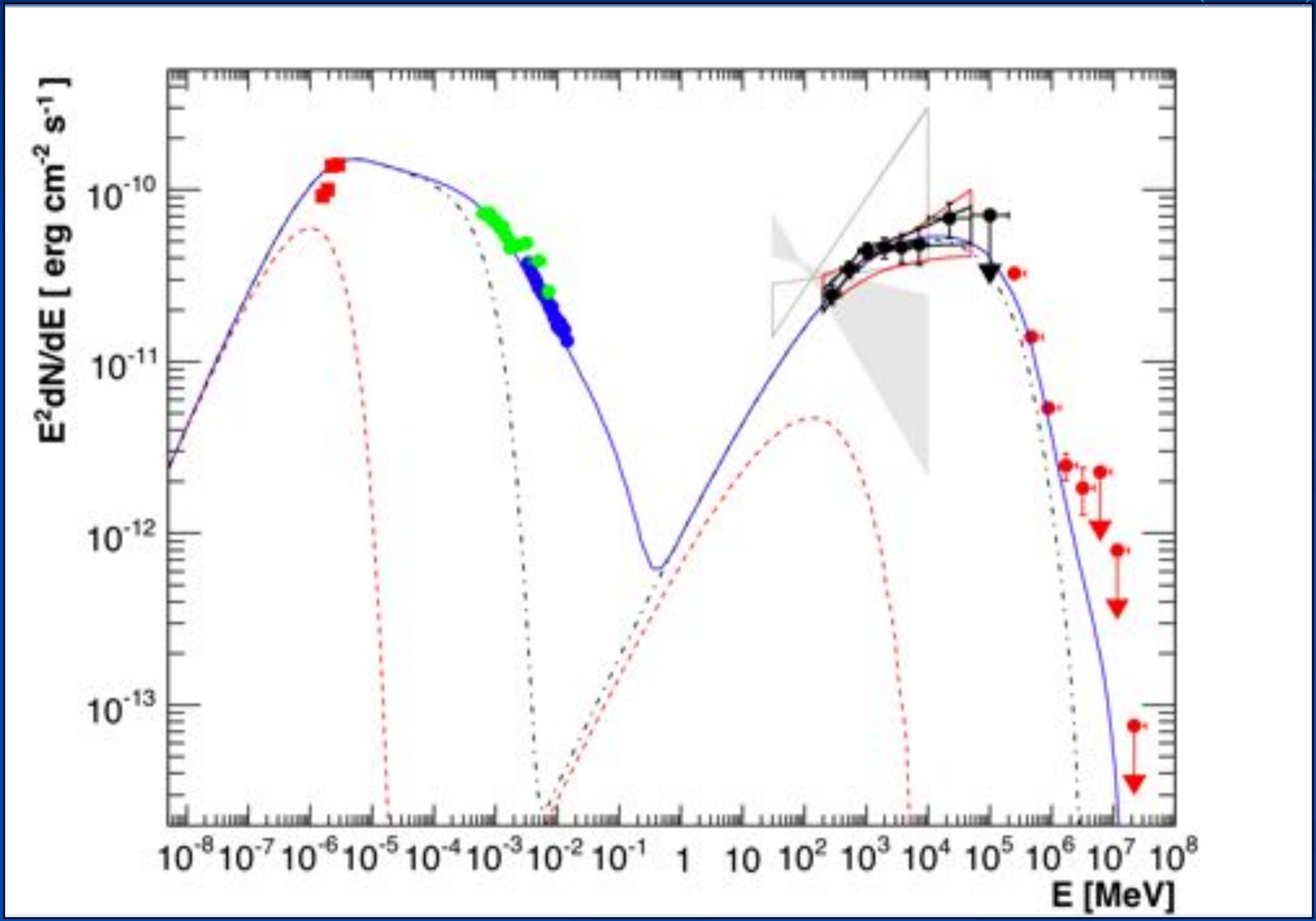
Multi-wavelength Low-state SED: *Fermi*-LAT Blazar PKS 2155-304

z=0.116

Abdo et al. (2009)

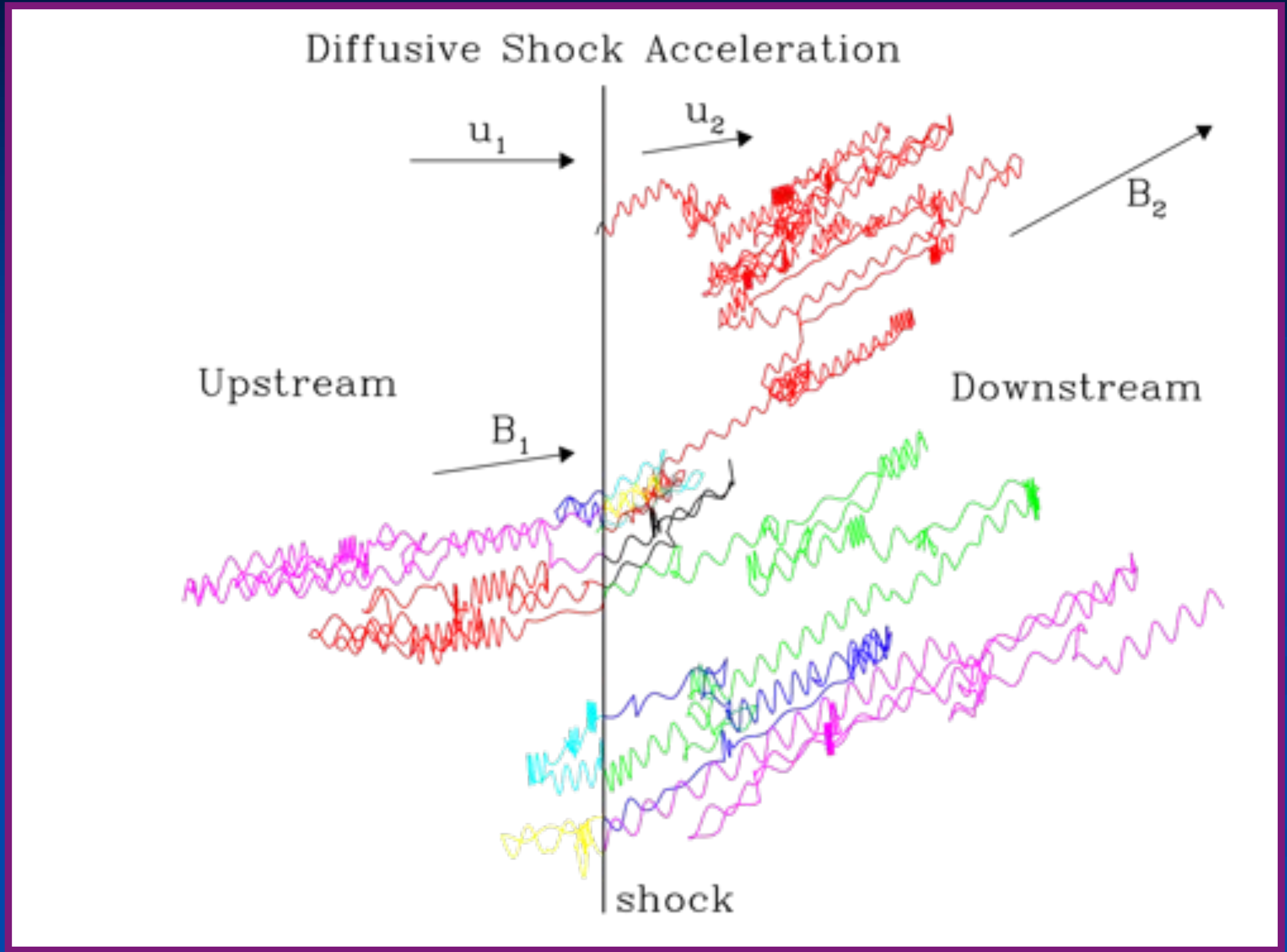


HBLs vs. FSRQs; breaks in LAT-band complicate things – e.g. 3C 454.3

Shock Acceleration: Monte Carlo Simulations

- The Monte Carlo simulations use a kinetic description of convection and diffusion in MHD shocks;
- Thermal ions and e^- are injected far upstream of shock;
- Particle diffusion in MHD turbulence is phenomenologically described via the mean free path λ being proportional to some power of its gyroradius r_g;
- Principal advantages include addressing large momentum ranges => excellent for astrophysical problems.
- Simulations are fully relativistic, and not restricted to subluminal shocks, and include shock drift acceleration;
- Technique is well-tested in heliospheric contexts with spacecraft data Earth's bow shock (Ellison et al. 1990) and interplanetary shocks (Baring et al. 1997; Summerlin & Baring 2006).
- Magnetic turbulence can be incorporated (Ostrowski et al.), though plasma effects cannot be fully modeled.

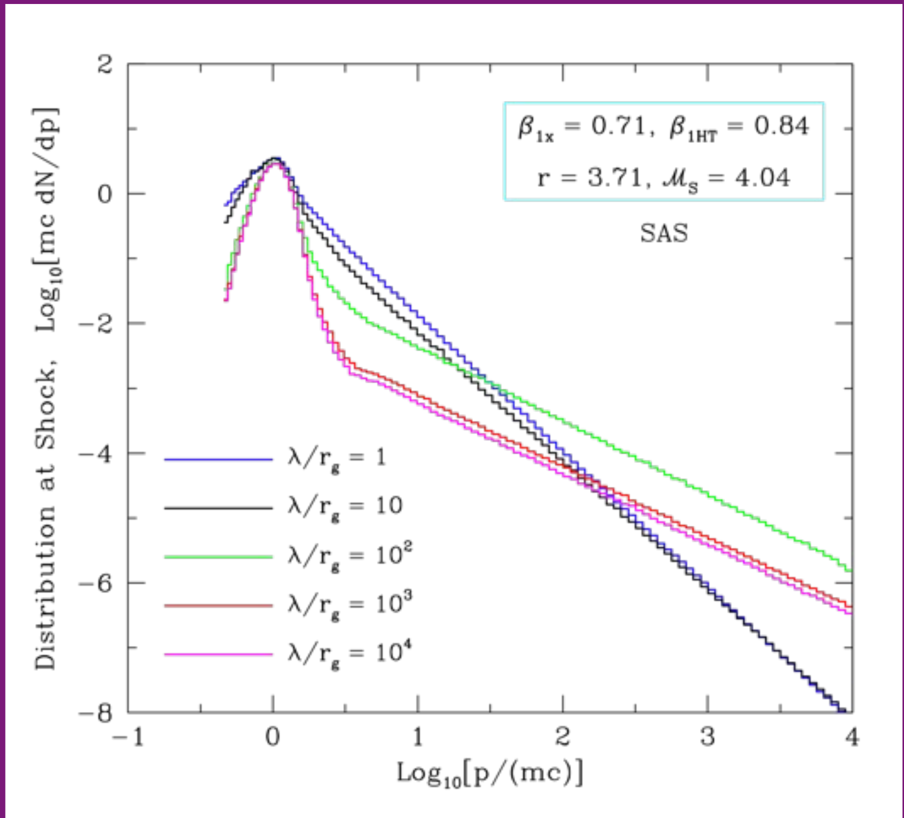
Monte Carlo Simulation Particle Trajectories

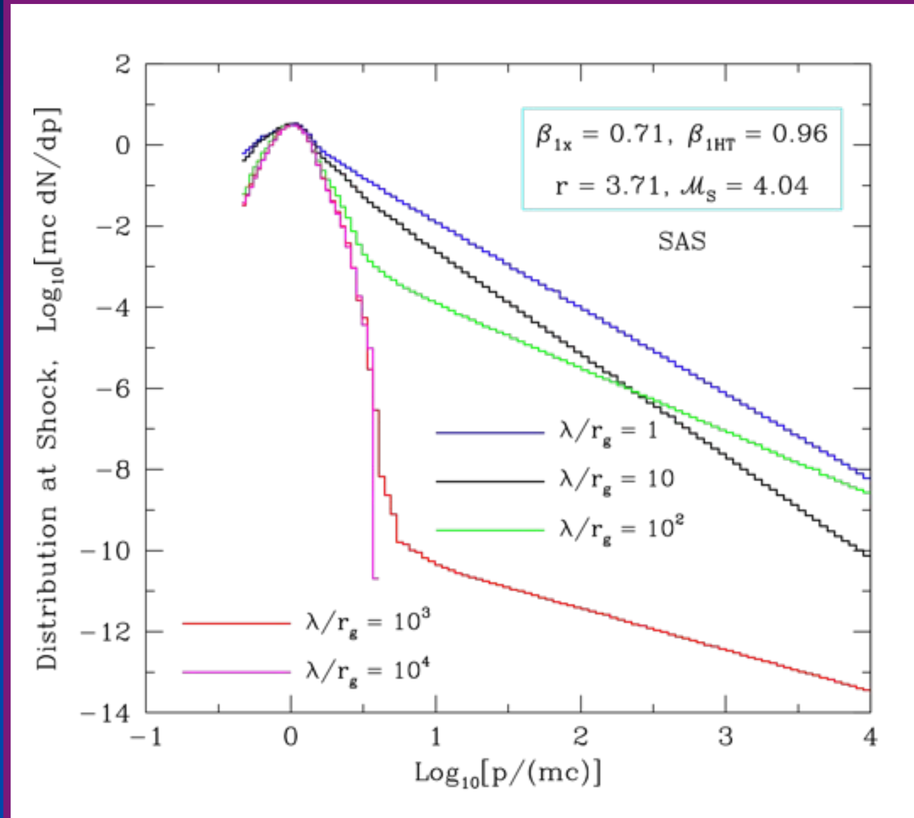


- Gyration in B-fields and diffusive transport modeled by a Monte Carlo technique; color-coded in Figure according to fluid frame energy.
- Shock crossings produce net energy gains (evident in the increase of gyroradii) according to principle of first-order Fermi mechanism.

Shock Acceleration Injection Efficiencies

Summerlin & Baring (ApJ, 2012)

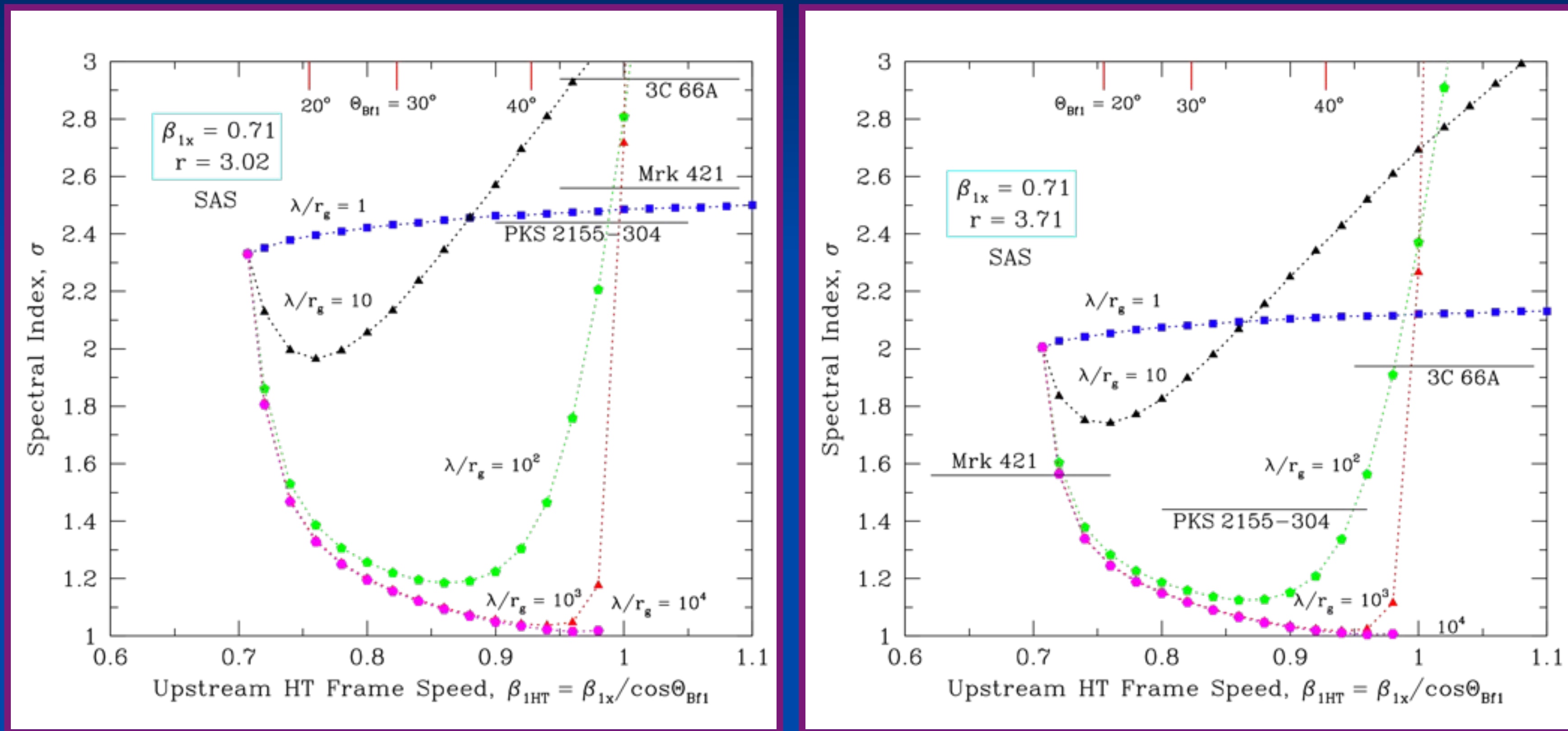




- *Left panel:* **moderately subluminal shocks;**
- *Right panel:* **marginally subluminal shocks;**
- **While flat distributions are realized for large λ/r_g regimes, the price paid is a dramatic reduction in injection efficiency.**

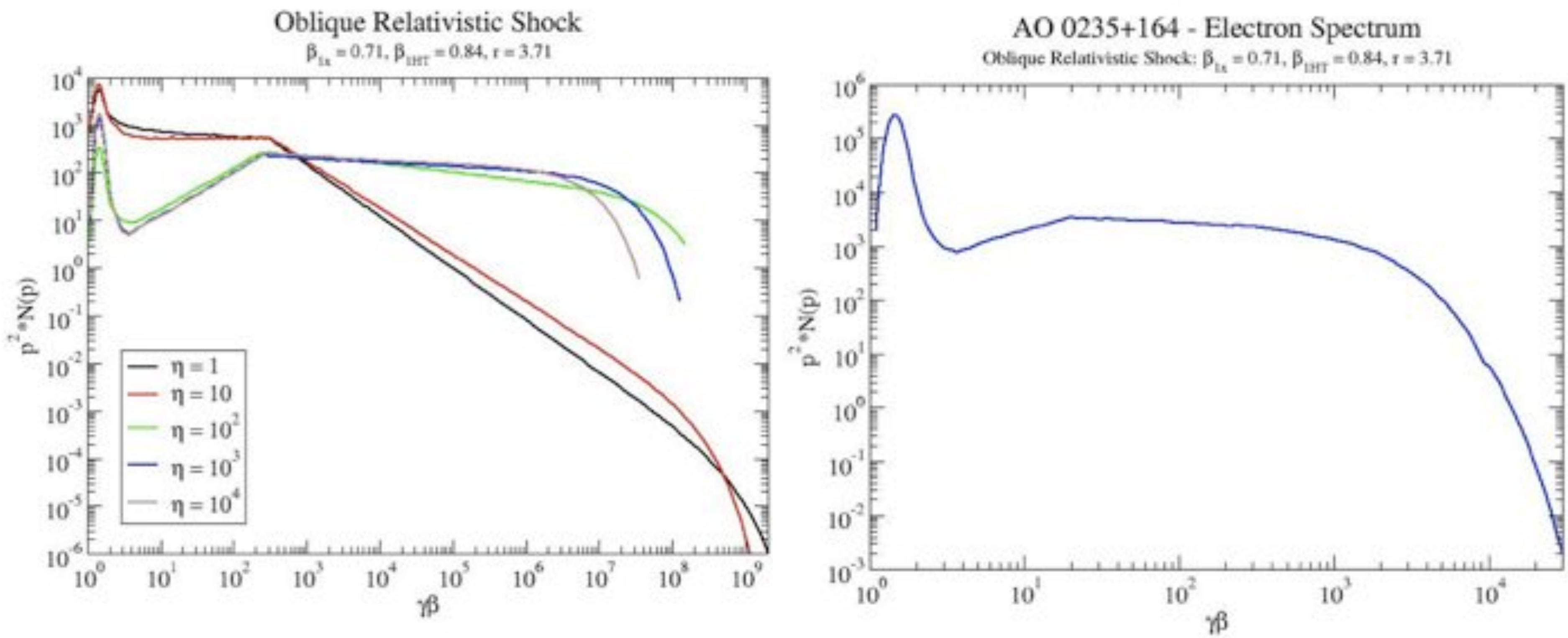
Acceleration Indices: Oblique Shocks

Summerlin & Baring (ApJ, 2012)



Left panel: **For uncooled blazar synchrotron/IC/SSC emission picture, superluminal shock regime is preferred.**
Right panel: **Cooled blazar (and GRB) scenarios require either strong turbulence, or subluminal shocks.**

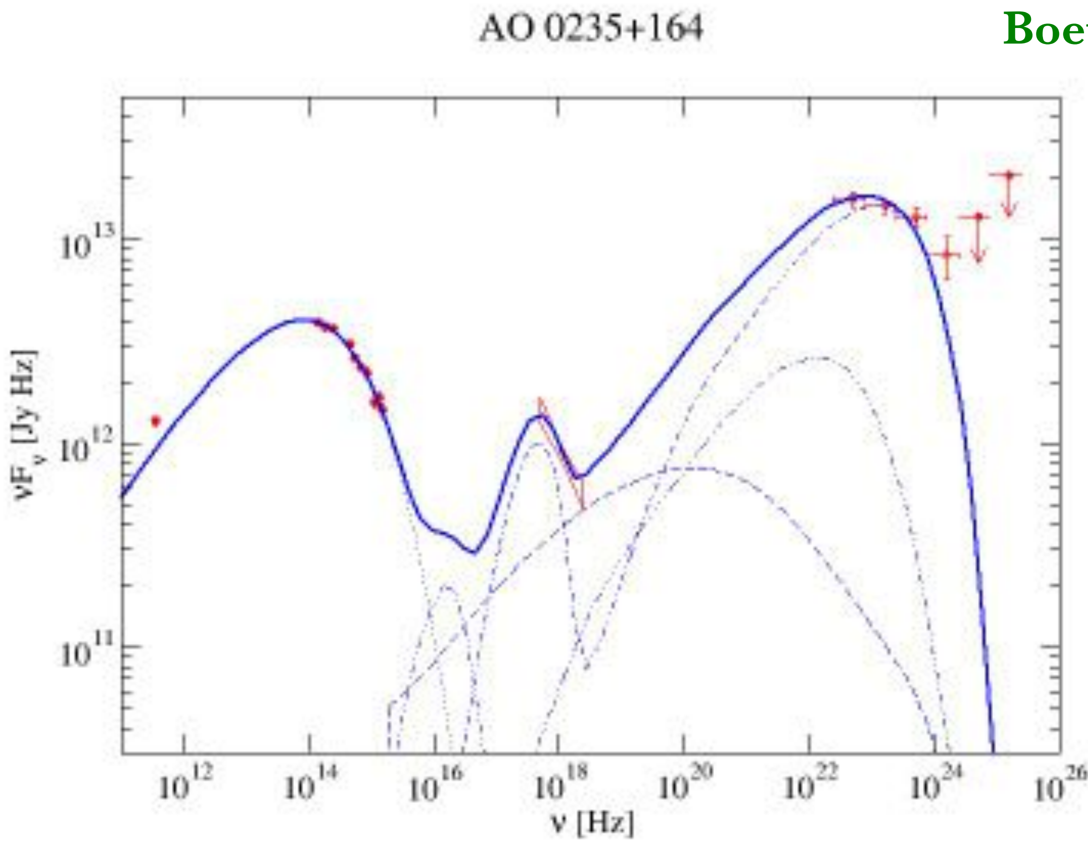
Lepton Distributions for Strong Cooling



- *Left panel*: Electron spectra in a mildly relativistic, oblique shock for various turbulence levels ($\eta=\lambda/r_g$);
- *Right panel*: Distribution tailored for multiwavelength spectral fit to the blazar AO 0235+164, with γ_{max}~10^4 (large η).

Multiwavelength SSC/EC fits to AO 0235+164

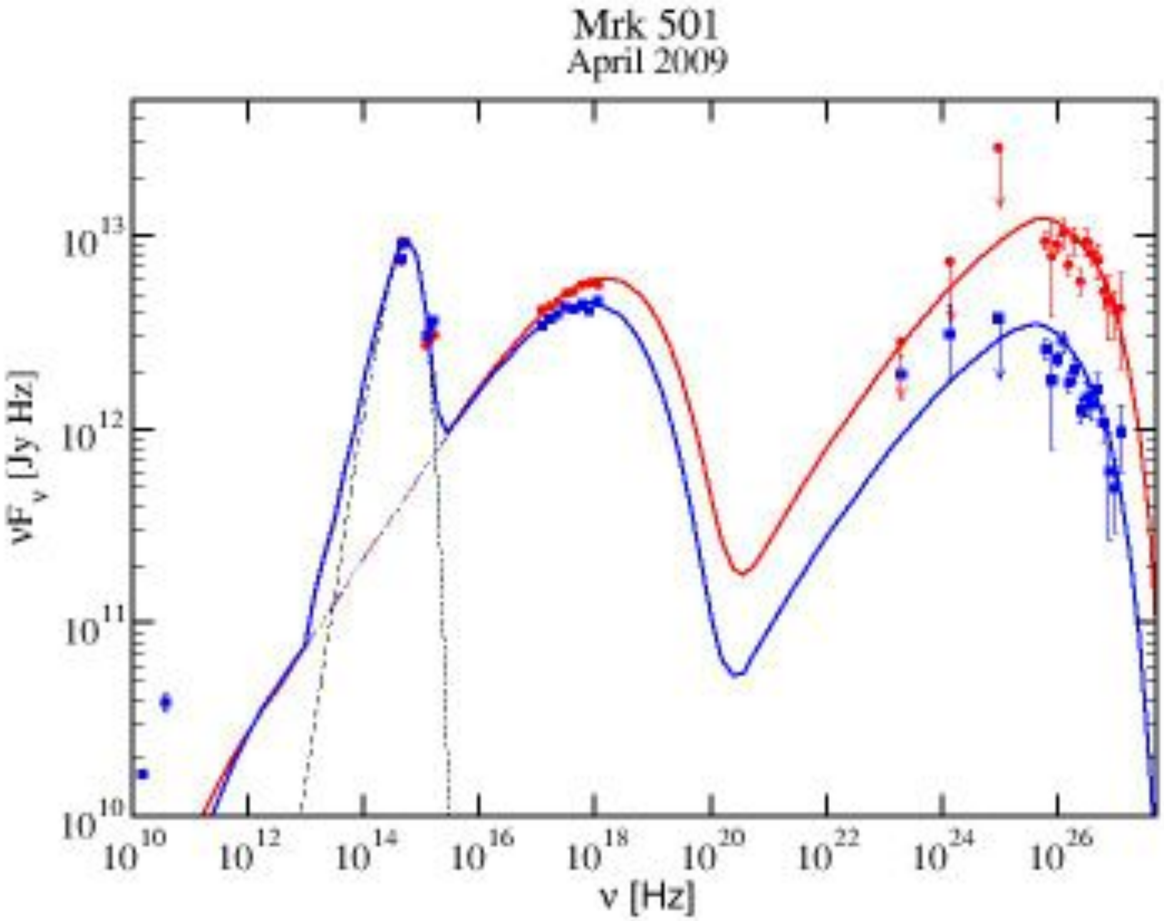
Boettcher et al. (2012)



Fermi data paper:
Ackermann et al.
(**2012: ApJ, 751, 159**)

- Diffusive shock acceleration (DSA) with active synchrotron+IC cooling;
- BL Lac object AO 0235+164 is pathological: synchrotron cannot fit X-rays
- Thermal population (present in DSA) rears it head in the X-rays;
- Large η ($\sim 10^8$) needed to move synchrotron peak to optical: $E_{max} \sim mc^2/(\eta\alpha_f)$

Multiwavelength SSC fits to Mrk 501

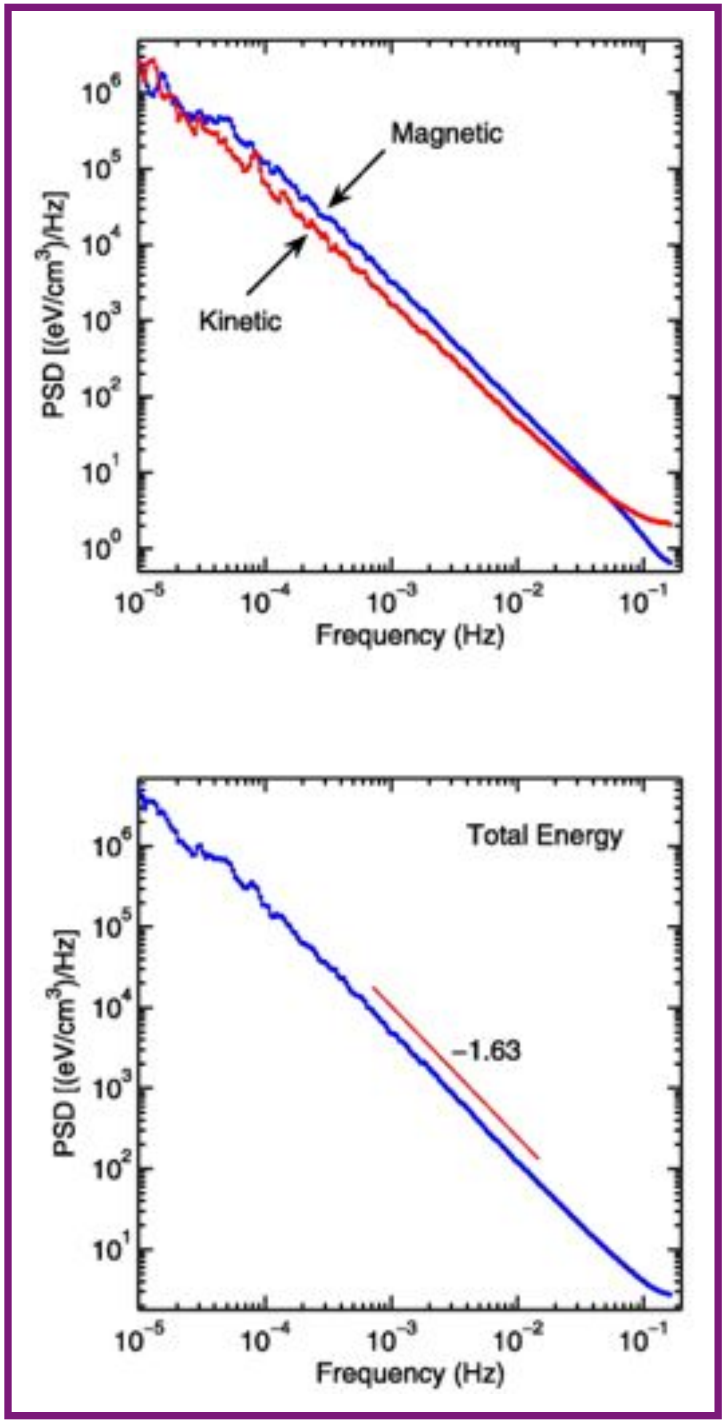


Fermi/TeV data: Acciari et al. (2011: ApJ, 729, 2)

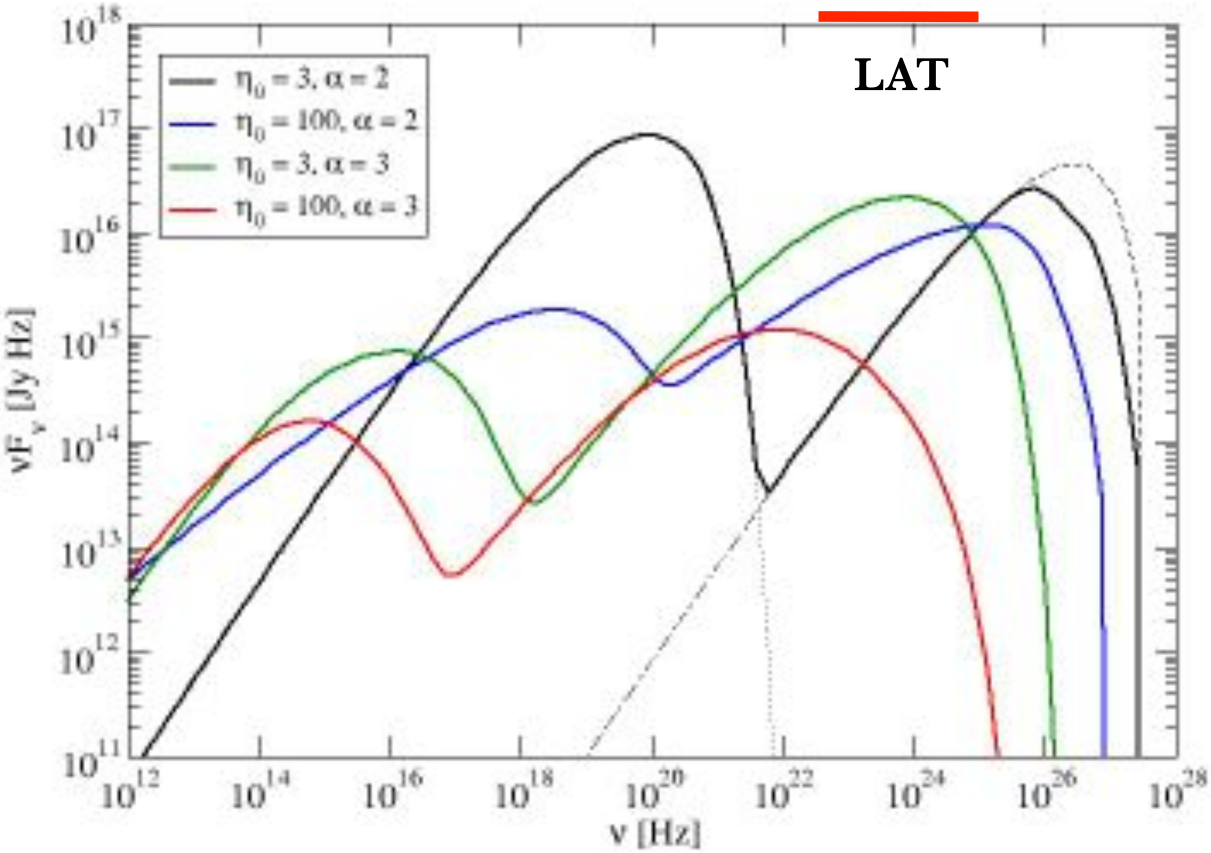
- Diffusive shock acceleration (DSA) with active synchrotron+IC cooling;
- Synchrotron cannot fit optical; disk component added.
- Large η ($\sim 10^4$) needed to move synchrotron peak into X-rays (for HBLs).
- Need for large $\eta = \lambda / r_g$ in blazars identified by Inoue & Takahara (1996).

Wind: Magnetic and Kinetic Turbulence in quiet Solar Wind at 1 AU

- *Podesta, Roberts & Goldstein (2007, ApJ 664, 543)*
- Wind spacecraft power spectrum for (quiet) solar wind turbulence: 81 days, 11/15/00 – 02/01/04 in 3 sec intervals;
- Inertial range above ~$3\mathrm{x}10^{-5}$ Hz;
- Magnetic $<(\delta B)^2/8\pi>$ spectrum (blue) and kinetic $<\varrho(\delta v)^2/2>$ power (red);
- Doppler resonance condition $\omega = \Omega/\gamma$ may not be satisfied by charges with large gyroradii;
- => increase of diffusive mean free path parameter $\eta = \lambda/r_g$ at large momenta.



Template SSC Spectra for Variable $\eta=\lambda/r_g$



- Cooled SSC spectra for shock acceleration with $\eta=\eta_0\ (p/p_0)^{\alpha-1}$, with α=2, 3.
- Here $\lambda \propto p^{\alpha}$. Windows where synchrotron peaks and IC peaks emerge depend substantially on choice of α, i.e. momentum dependence of λ.
- Spectral index in Fermi-LAT band also depends on choice of α .
- => X-ray/γ-ray diagnostics on turbulence power spectra and particle diffusion.

Conclusions

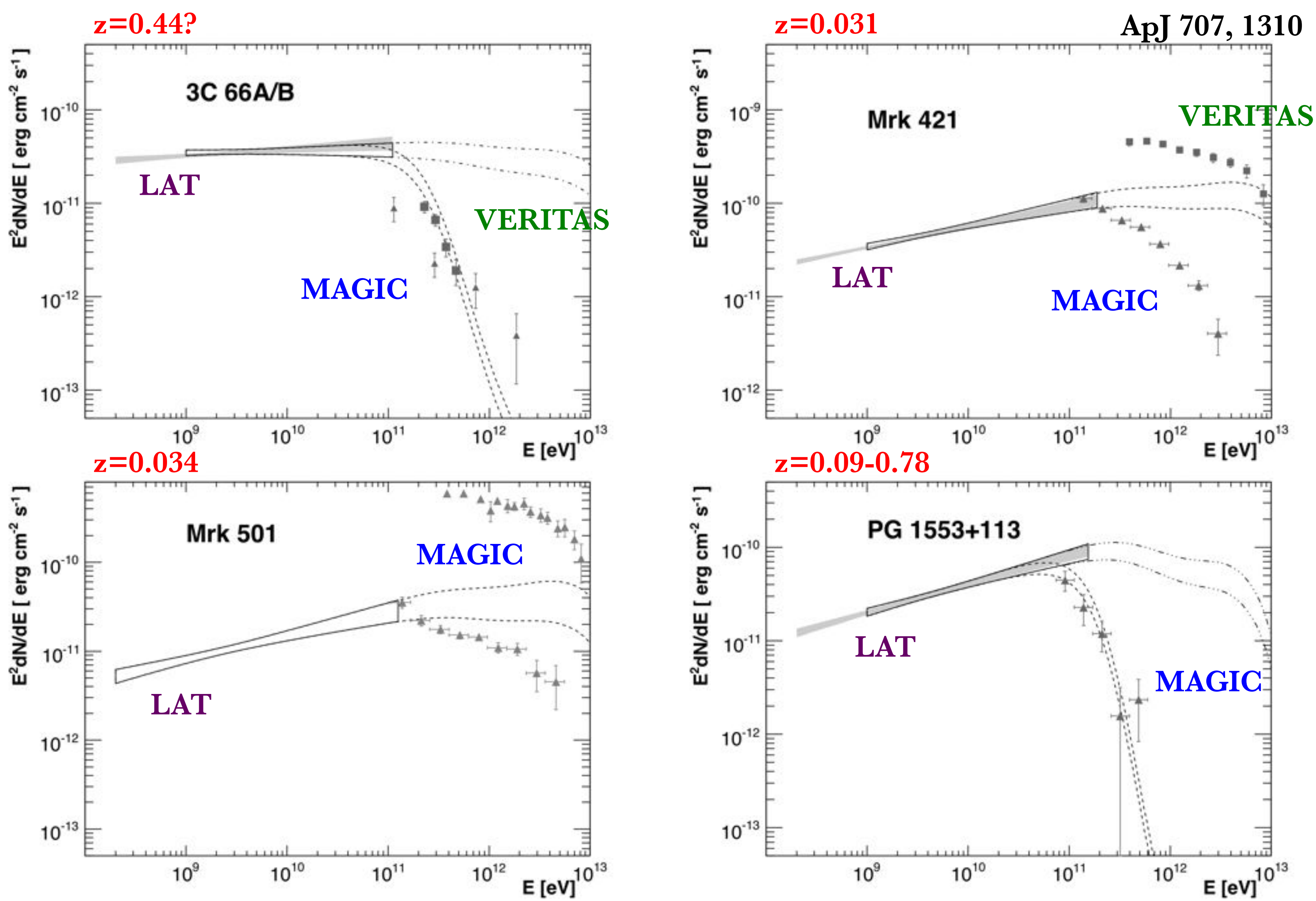
- Shock acceleration particle indices depend on several parameters: **field obliquity**, the **scattering strength** or level of MHD turbulence, **amount of diffusion across B**;
- So, blazar spectra are intimately connected to detailed shock parameters => *Fermi* role for gamma-ray spectral diagnostics for leptonic and hadronic models.
- Index parameter space dichotomizes into *subluminal* (flat) and *superluminal* (steep) regimes.
- Cooling models: several LAT-TeV blazars indicate ***subluminal*** acceleration regimes; 3C 279 is exception.
- We expect $\eta=\lambda/r_g$ to be an increasing function of p as scales sample greater distances from the shock.
- M/W spectra: X-ray/γ-ray diagnostics on turbulence power spectra and particle diffusion (coming soon).

Connecting to Blazar Gamma-ray Observations:

- Model coupling between particle acceleration index σ for $dn/dp \propto p^{-\sigma}$ and observed photon index β ($dn_\gamma/d\varepsilon_\gamma \propto \varepsilon_\gamma^{-\beta}$) depends on whether in situ cooling is efficient or not.
  - Index data is acquired by Fermi-*LAT*, not absorbed TeV band
- Three main possibilities for blazars:
  - Uncooled synchrotron or IC/SSC: $\beta=(\sigma+1)/2 \Rightarrow \sigma=2\beta-1$
  - Strongly-cooled synchrotron or IC/SSC: $\beta=(\sigma+2)/2 \Rightarrow \sigma=2\beta-2$
  - Uncooled hadronic emission: $\beta\sim\sigma$
- => Great diagnostics potential in *Fermi* era!
- Several LAT blazars with $\beta=\Gamma_h<2$ may require *subluminal* shocks, perhaps with weak turbulence. 3C 279 with its steep spectrum is an exception, perhaps sampling *mildly-superluminal* shocks with strong turbulence.

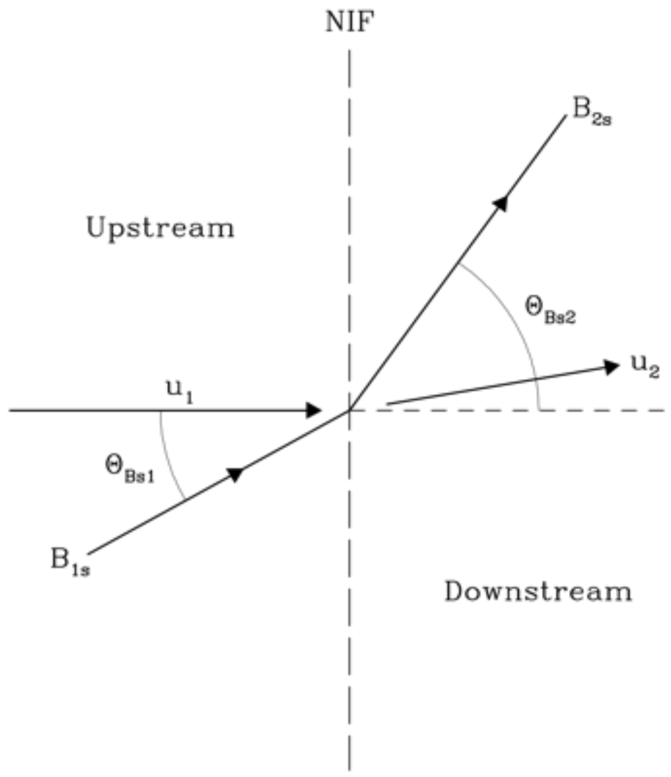
Fermi LAT + TeV Blazars

Abdo et al. '09
ApJ 707, 1310

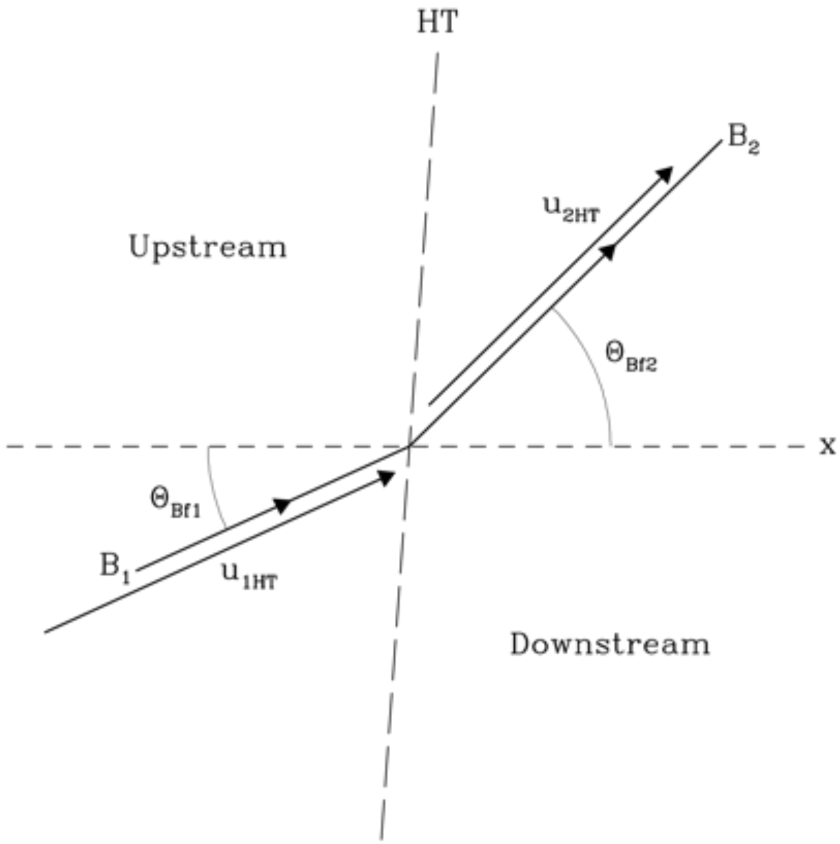


Oblique Relativistic MHD Shock Geometry

Particle retention in the shock layer is extremely sensitive to the magnetic field angle w.r.t. the shock normal in relativistic shocks.

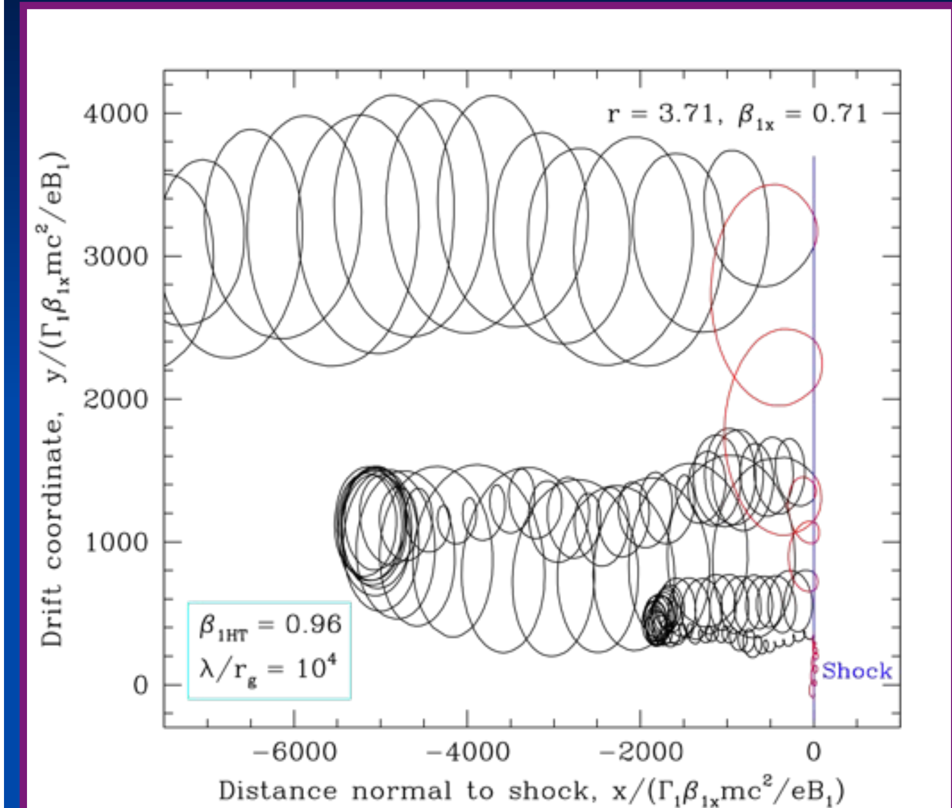


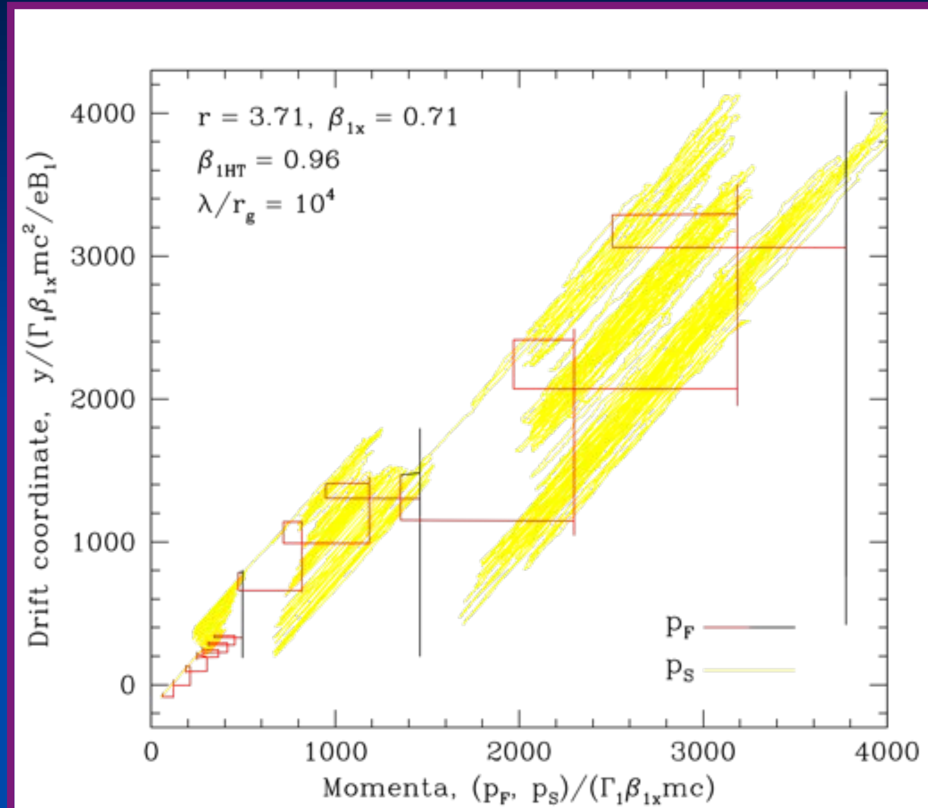
Normal Incidence Frame (NIF)



de Hoffmann-Teller frame (HT)

Shock Drift Acceleration in Action: $\lambda/r_g=10^4$





- From Summerlin & Baring (2012) - *Left Panel*: projection of a selected ion orbit onto the x-y plane, exhibiting drifting in the shock layer. *Right Panel*: evolution of magnitudes of momentum in fluid (p_F) and shock (p_S) frames versus y, indicating shock drift episodes interspersed with upstream diffusive hiatuses in energy gain;
- Lowering λ/r_g rapidly degrades the contribution of shock drift, enables particle convection downstream, and steepens spectrum.
- Just like shock drift acceleration in non-relativistic investigations:

Spectral Properties of Diffusive Relativistic Shock Acceleration

- For small angle scattering, ultra-relativistic, parallel shocks have a power-law index of 2.23 (Kirk et al. 2000);
- Result obtained from solution of diffusion/convection equation and also Monte Carlo simulations (Bednarz & Ostrowski 1996; Baring 1999; Ellison & Double 2004);
- Power-law index is **not universal**: scattering angles larger than Lorentz cone flatten distribution;
- Large angle scattering yields kinematic spectral structure;
- In *superluminal* shocks, spectral index is generally a strongly *increasing* function of field obliquity angle Θ_{Bn1}.